U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: TURBINE ENGINE POWER-LOSS AND INSTABILITY IN EXTREME CONDITIONS OF RAIN AND HAIL

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Change:

1. PURPOSE. This advisory circular (AC) provides guidance and acceptable methods, but not the only methods, that may be used to demonstrate compliance with the requirements contained under Title 14 of the Code of Federal Regulations (14 CFR), part 33, §§ 33.78(a)(2), and 33.78(c). Section 33.78(a)(2) requirements pertain to the operation of turbine engines in extreme rain and hail, and § 33.78(c) pertains to engines installed on supersonic airplanes. While the guidelines in this AC are not mandatory, they are derived from extensive Federal Aviation Administration (FAA) and industry experience in determining compliance with the requirements.

2. BACKGROUND. In 1988, the Aerospace Industries Association (AJA) initiated a study of airplane turbine engine power-loss and instability phenomena that were attributed to operating in inclement weather. AIA, working with the Association European des Constructeurs de Materiel Aerospatial (AECMA), concluded that a potential flight safety threat exists for turbine engines installed on airplanes when operating in an extreme rain or hail environment. AIA and AECMA further concluded that the rain and hail ingestion requirements contained in § 33.77 did not adequately address these threats. Consequently, the Federal Aviation Administration (FAA) and the Joint Aviation Authorities (JAA) have promulgated additional rain and hail ingestion standards.

3. DEFINITIONS. The following terms are defined for the purpose of this AC.

a. Auto-recovery systems. Auto-recovery systems typically include auto-relight systems, stall recovery systems, or any other engine system intended to recover the operability of an engine following a flameout or surge/stall.

b. Critical **point(s)**. Operating conditions within the engine flight envelope at which an engine's operability margin is reduced to a minimum level. Operability margin includes compressor surge and stall margin, fuel control run-down margin, combustor **flameout** margin and instrumentation sensing errors.

c. Flameout. Any extinction of flame within the combustor, and if there is no subsequent operator or auto-recovery system intervention, generally results in a run-down and ultimately a shutdown of the engine.

d. **Hail**. Water in a solid granular state, either in its naturally occurring form or in a fabricated form, for the purpose of testing engines.

e. Hail water content **(HWC)**. The concentration, in the air, of water in the form of **hail,** expressed in grams of hail per cubic meter of air.

f. Rain. Water in liquid droplet state, either in its naturally occurring form, or created artificially by discharging water **from** spray nozzles for the purpose of testing engines.

g. Rain water content **(RWC)**. The concentration, in the air, of water in the form of rain, expressed in grams of rain per cubic meter of air.

h. Run-down. The uncommanded reduction of engine rotor speed that will result from the fuel control steady state operating line coinciding with the fuel control acceleration schedule.

i. Scoop **factor**. The ratio of nacelle inlet (highlight) area to the area of the captured air stream tube (Scoop factor = A_h/A_c). (Refer to FIGURE 1-1).

j. **Stall**. An airflow breakdown at one or more compressor airfoil stages

k. **Surge**. Response of an entire engine that is characterized by a significant **airflow** stoppage or reversal in the compression system.

l. Sustained **power** or thrust loss. A permanent reduction in power or thrust at the engine's primary power set parameter (e.g., rotor speed, engine pressure ratio, torque, shaft horsepower).

NOTE: For the purpose of this AC, "part 33, Appendix B" will be referred to as Appendix B with the associated Table(s) and Figure(s) only.

4. DISCUSSION. The arrangement of this AC is in five Sections. Section 1 provides an overview of the power-loss and instability phenomena associated with operating airplane turbine engines in extreme rain or hail. Section 2 elaborates on some of the turbine engine design aspects that affect engine operability in rain or hail. Sections 3 and 4 describe acceptable methods for demonstrating that the engine type design will operate acceptably throughout its operating envelope when exposed to the identified rain and hail threats. Finally, Section 5 provides guidance relative to § 33.78(c), titled, Engines for Supersonic Airplanes.

SECTION 1. POWER-LOSS AND INSTABILITY PHENOMENA

5. GENERAL. There have been multiple engine power-loss and instability events, forced landings, and accidents attributed to turbine engine malfunction in extreme conditions of rain or hail. Investigations have revealed that ambient concentrations of rain and hail can be amplified significantly through the engine core at certain combinations of flight speed and engine power or thrust condition. In some instances, the resulting increased amounts of ingested rain and hail have been **sufficient** to produce engine anomalies such as surging, power loss, and engine flameout.

6. METEOROLOGICAL DATA. Appendix B, defines the atmospheric conditions of rain and hail for the purpose of establishing certification test standards. Note that the water concentrations defined for rain and hail in Appendix B represent ambient conditions, not test conditions at the engine inlet.

7. **RAIN** AND HAIL CONCENTRATION AMPLIFICATION AND ATTENUATION EFFECTS. During in-flight encounters with rain and hail, changes in engine power or thrust and flight speed can alter the rain or hail concentration within the engine for any given atmospheric rain or hail content.

a. Scoot, Factor Effect (Refer to FIGURE l-l). The inlet-capture stream tube for **airflow** varies widely across the spectrum of engine power and flight speed. At low engine power and high flight speed, the air intake requirements are minimal in comparison to the available ram air. Consequently, a significant portion of the air in front of the inlet spills outside the inlet lip (see FIGURE l-l). The scoop factor increases with decreasing engine speed and increasing aircraft speed. This factor occurs due to the increase of inlet airflow spillage, resulting from a smaller captured air stream tube. Due to their mass, large rain droplets and hail are relatively **unaffected** by this spillage, and will be captured by the inlet. The inlet area will establish the amount of rain or hail captured through the **inlet**. The amount of this amplification effect is equal to the ratio of the nacelle inlet water capture area (Ah) to the stream capture tube, air capture area **(A_c)**. Bypass turbofan engines may have an additional internal scoop factor effect due to the divergence of the engine core stream tube from the nacelle inlet to the core inlet at low engine power and high flight speed. Therefore, the scoop factor effect generally results in concentration amplification, the amplification is greatest when high flight speed is combined with low power or thrust.

b. Relative velocity centrifuging effects. Some of the rain and hail will be centrifuged away from the engine core by a fan and, to a lesser extent, away from the engine by a propeller. This beneficial effect is dependent upon the fan or propeller geometry and rotational speed, inlet design and location, engine design, aircraft velocity, and on the size of the rain droplets and hailstones.

(1) Turbofan and turbojet engines (Refer to FIGURE l-2).

(a) Rain. The inlet diffusing flow field pressure gradients act to shear large droplets into small droplets that decelerate and enter the fan at velocities close to the inlet air velocity. As shown in FIGURE l-2, the majority of droplets that enter the engine at gas path speeds will strike the fan and be centrifuged away from the engine core. The forces acting upon the rain droplets in-flight will vary with airplane velocity and altitude. A portion of the rain droplets entering the engine may have sufficient mass, such that deceleration to gas path velocity is not possible. At low engine rotational speeds and high flight speeds, the velocity of the large rain droplets, relative to the fan, may allow that portion of the rain droplets to pass through the fan without impact (refer to hail velocity vector diagram in FIGURE l-2) and could possibly result in higher water concentrations in the engine core.

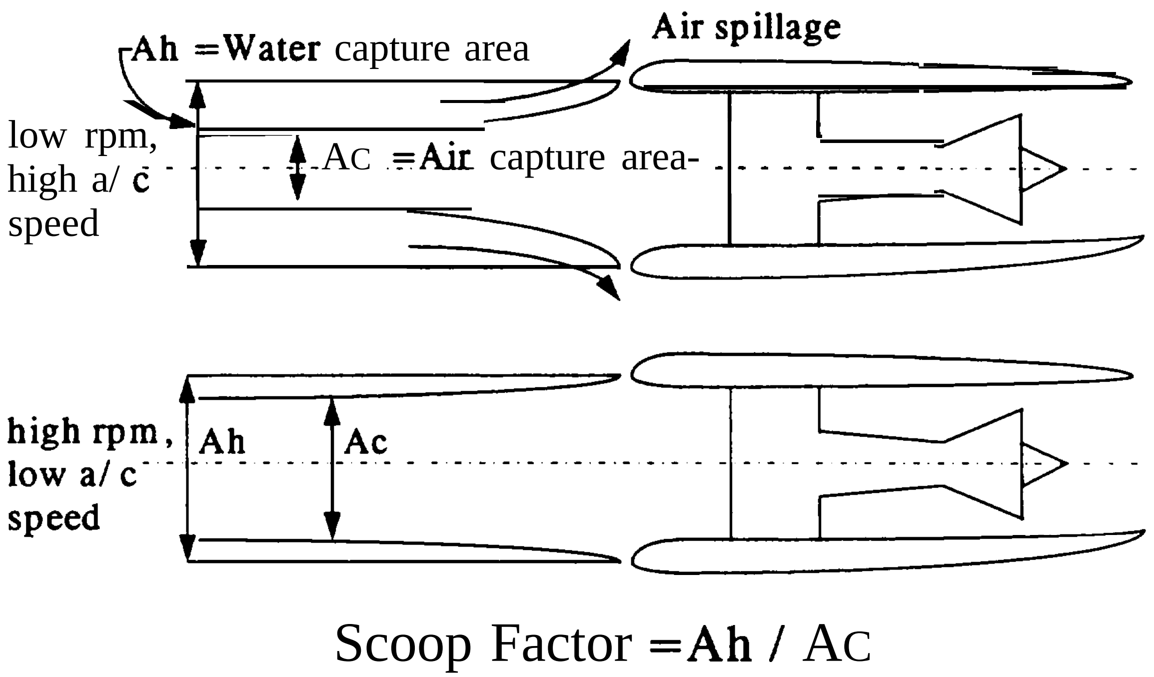


FIGURE l-l. Scoop Factor

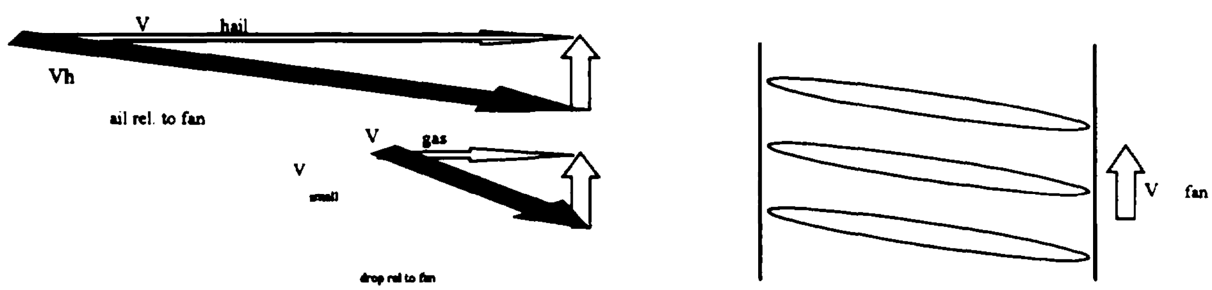
FIGURE 1- 1: The first drawing shows the inlet air spillage at low engine rpm/high aircraft speed increases engine face water/air ratio, and the second high engine rpm/low aircraft speed decreases engine face water/air ratio by reducing air spillage.

(b) Hail. Hail particles will maintain their size and will not be significantly affected by the engine inlet flow field. Consequently, the hail particles will enter the engine close to aircraft speed. At low engine rotational speeds, a significant portion of the hail particles (similar to large rain droplets) may pass through the fan without impact (see FIGURE l-2) and could possibly result in high hail concentrations in the core.

(2) Turboprop engines.

(a) Rain. When compared to a turbofan engine, the inlet flow field effect of the propeller on both the droplet size and the relative velocity centrifugal effects are reduced because of the lower solidity of the propeller. Conducting this type of test without the propeller, either by using some other load-absorbing device or running the gas generator alone, normally results in an added degree of conservatism. Unlike turbofan engines, the propeller rotational speed does not vary significantly in flight, regardless of power setting. Therefore, any beneficial effect of the propeller will remain reasonably independent of altitude and power setting. Where an inlet particle separation system is incorporated, credit may be taken for its characteristics.

(b) Hail. As with rain, the effects of the propeller on hail ingestion are generally considered beneficial, since it reduces the effective core concentrations. Therefore, conducting a hail test without the propeller should result in an added degree of conservatism. Another consideration is the effect of the propeller spinner. In a continuous hail encounter, the spinner may redirect hail into the general area of the engine intake. The trajectory of this material will influence the effective inlet concentration to the engine, and should be included in any supportive analysis for other than full-scale powerplant tests.



• Rain Breaks Up Into Smaller Droplets as They Slow in Inlet • Hail Not Affected/Slowed • Hail Enters Booster With Near Perfect Match of Blade * Rain (Small Droplets) Centrifuged Away From Booster, Less Enters Core

FIGURE l-2. Velocity Vector Diagram

8. ROTORCRAFT TURBINE ENGINES. For rotorcraft applications, testing to the requirements of § 33.78(a)(2) may be replaced by the static rain ingestion test specified in § 33.78(b). While it may be possible to define in-flight rain and hail ingestion concentration amplification and attenuation effects for rotorcraft installations in a similar manner to airplane installations, the effects are typically small. When rotorcraft applications are compared to airplane applications, the proportionately

higher engine power setting during descent, and the lower flight speeds of the rotorcraft results in a small scoop factor effect. Rotorcraft turbine engines may not have rotating components that centrifuge rain or hail away from the engine. While differences in centrifuging capabilities between static test conditions and flight operations is an important consideration for turbofan engines, it typically has no applicability to rotorcraft turbine engines. Consequently, increasing the ambient rain concentrations in Appendix B to four-percent water (droplet flow to airflow) by weight, will usually compensate for any flight effects.

9. TURBINE ENGINE OPERABILITY EFFECTS. As stated previously, rain and hail ingested into a turbine engine can be at greater than ambient concentrations in the engine when at certain combinations of flight speed and engine power condition. Ingestion of water through the engine core can produce a number of engine operational anomalies, including compressor surge, power or thrust loss, and flameout. These operational anomalies are partly a result of the changes in the thermodynamic cycle of the turbine engine because of the ingestion of water during rain or hail.

a. Compressor rematch. The presence of rain or hail particles, or water from melted hail in the gas path causes the compressor to assume new operating conditions. The net overall effect may result in an increase to the compressor operating line, with a corresponding decrease to the compressor surge line and stall margins.

b. Engine control response (Refer to FIGURE 1-3). As shown in FIGURE 1-3 of this AC, the fuel control steady-state operating line will move upward toward the acceleration schedule as the amount of ingested rain or hail increases. A higher operating line means that more fuel is required to sustain steady-state operation. When the operating line coincides with the acceleration schedule, the fuel control may be unable to deliver additional fuel to accommodate the increasing rain or hail ingestion. Under this condition, the engine may run-down and could result in sub-idle engine operation, a loss of throttle response, or flameout.

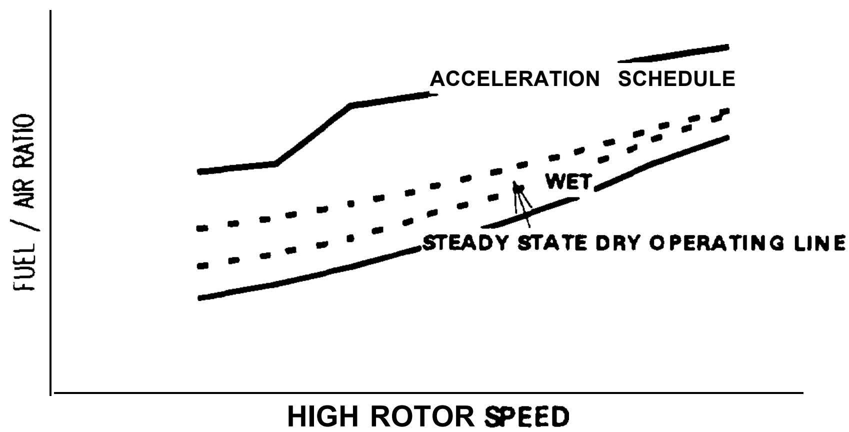


FIGURE l-3. Typical Engine Control Characteristics

c. Combustor response. The evaporation in the combustor of liquid water resulting from the ingestion of rain or hail, will cause a reduction in combustor flame temperature and will adversely affect combustor performance. The reduced temperature will result in slowing of the chemical reaction rate and inhibit complete combustion, further resulting in reductions of both combustor efficiency and stability. Typically, the combustor is most susceptible to flameout when it is required to operate at a sub-idle operating condition. Therefore, a flameout condition may be preceded by an engine run-down as discussed previously in paragraph 9.b.

10. CASE CONTRACTION. As rain or hail is ingested into the engine, the temperature of the compressor case may decrease at a faster rate than the compressor rotor. This would result in a reduction in compressor blade tip clearances, and may result in blade tip rubs. Turbine engine types, such as turbojets that have a sign&ant scoop factor effect, but lack design features to direct rain or hail away from the engine core (e.g., fan blades, bypass splitter, etc.), may be more susceptible to damage resulting from case contraction.

SECTION 2. DESIGN FACTORS

11. **GENERAL**. The response of a turbine engine to a rain or hail encounter depends on a number of design and operational factors. The manufacturer can greatly improve the operability of the engine during an extreme rain or hail encounter by incorporating certain design features. However, there may be a compromise between some of these design features. For instance, a spinner designed to maximize hail rebound and rain droplet **centrifuging**, may also result in a spinner which is more susceptible to large ice accretions.

12. DESIGN FEATURES. With knowledge of the power-loss and instability phenomena, the applicant can incorporate design features that increase the engine's tolerance to rain and hail.

a. Fan blade or nrooeller design and **operating speeds**. The fan blade or propeller, under the right conditions, can effectively centrifuge small droplets of rain away from the engine core. Hail particles and large droplets of rain can also be centrifuged or deflected away from the engine core by the fan blade or propeller, but with considerably less effectiveness. The applicant should consider the relative velocity effects at the critical points when establishing fan blade or propeller geometry and operating speeds.

b. **Spinner** or nose cone. A spinner or a nose cone can effectively deflect rain and hail away from the engine core. Designing the spinner or **nosecone** to maximize hail deflection, requires knowledge of the post impact trajectory characteristics of hail particles.

c. **Bypass** solitter. In the case of turbofan engines, increasing the gap between the fan blade trailing edge and the bypass splitter generally tends to enhance the benefits to the engine core **from** the centrifugal effects of the fan blade.

d. Engine air bleeds. Engine air bleed ports provide a direct means of redirecting or extracting rain and hail away from the engine core, and a direct means of improving compressor surge and stall margins. The effectiveness of the bleed in extracting liquid water or hail particles out of the engine core will depend on; the radial distribution of the water or hail particles, the location of the bleed, the bleed entrance geometry, and the bleed control logic. Also, in the case of hail, the bleed should be designed to minimize the likelihood of clogging and blockage.

e. Engine and aircraft accessory loads. Accessory loads will tend to move the fuel control operating line closer to the acceleration schedule. Therefore, accessory loads should be minimized where possible while in rain and hail conditions.

f. Fuel control. Fuel controls that schedule fuel using a rate change of compressor speed, should provide a consistent acceleration and deceleration thrust response during rain or hail ingestion.

g. Variable stator vane. The schedule of the compressor variable stator vanes directly impacts the compressor performance, operability, and stability characteristics. Weather related sensing or scheduling errors may cause a loss of surge or stall margin.

13. OPERATIONAL FACTORS. With knowledge of the power-loss and instability phenomena, the applicant can establish an operating envelope that minimizes the power-loss and instability threats.

a. Increased power levels. Increasing engine power or thrust setting (i.e., throttle advance) will increase rotor speeds and air intake requirements. This is beneficial because an increase in rotor speed will tend to improve centrifuging, while an increase in airflow will tend to decrease the adverse scoop factor effect. The combustor stability margin will also be improved with an increased power setting.

b. Avoidance of engine transients. Avoidance of engine transients improves the stall and surge tolerance of the engine and reduces the likelihood of run-down, However, avoidance of throttle transients should not be used by the applicant to show compliance with the rain and hail ingestion requirements.

c. Decreased flight speeds. Reduced aircraft speed, like increased power levels, is beneficial because it improves centrifuging while decreasing the adverse scoop factor effect.

SECTION 3. CRITICAL POINT ANALYSIS

14. GENERAL. Compliance with the requirements of § 33.78(a)(2) is a two-step procedure. The first step is to identify, through analysis, the critical operating points for rain and hail ingestion. The second step is to test the engine at selected critical points to validate the engine's capability to adequately withstand extreme rain and hail encounters. The applicant should develop a critical point analysis and submit the analysis to the appropriate FAA Aircraft Certification Office (ACO) for concurrence, prior to rain and hail ingestion testing.

15. CRITICAL POINT ANALYSIS ELEMENTS. The purpose of the critical point analysis is to identify operating points within the engine flight envelope where operability margins are minimized due to the presence of rain or hail. The analysis should encompass the full range of all pertinent variables. These variables include, but are not limited to:

a. Atmospheric conditions. The rain and hail threats identified in Appendix B, FIGURE B 1 and Tables B 1 through B4, should be used for determining the critical atmospheric conditions used in the critical point analysis. The critical point analysis should consider the effects of nominal, as well as extreme levels of rain or hail on the function of all relevant engine components and systems.

b. Rain and hail concentration amplification and attenuation effects. The critical point analysis should quantify the amount of rain and, separately, the amount of hail ingested into the engine core. Therefore, amplification and attenuation effects, such as the scoop factor effect and relative velocity effect should be quantified. This may necessitate assessing a representative installation aerodynamic flow field and probable flight profiles. In the case of rain ingestion, droplet breakup characteristics need to be established or conservatively assessed. In the case of hail ingestion, the trajectories of hail particles after impacting nose cones, spinners, inlet surfaces, blades, and vanes etc., need to be established or conservatively assessed for determining critical points.

c. Engine power level. The entire envelope of power conditions should be analyzed. While run-down and flameout are predominantly low power anomalies, compressor stability problems could occur at high power.

d. Engine parasitics. The variability of engine parasitics, such as air bleeds and accessory loads, should be analyzed for their effect on the critical points.

16. CRITICAL POINT ANALYSIS PROCEDURE. The critical point analysis is an assessment of the engine's capability throughout its operating envelope, given the range of event variables described above and any engine operability condition which is **affected** by ingested rain or hail. Typical operability conditions to consider include; surge and stall margin, **fuel** control run-down margin, combustor **flameout** margin, and instrumentation sensing errors. The critical point analysis should also address case contraction.

SECTION 4. COMPLIANCE METHODS

17. GENERAL. An engine compliance test method consistent with the critical point analysis may include the use of a ground-level static facility. This method should include appropriate means to conduct engine tests during simulated rain and hail ingestion at the increased concentrations. This would simulate in-flight rain and hail scoop factor concentration amplification effects, and compensate for the differences between the critical point conditions and the ground level test conditions. Other possibilities for demonstrating compliance include; wind tunnel testing, direct core water-injection tests, component rig tests, scale model tests, and analyses.

18. TEST POINT SELECTION. The critical hail point(s) and rain point(s) that yield the least operability margin should be demonstrated by engine ingestion testing. Additional test points should be considered if any of the operability margins are determined to be minimal (e.g., compressor surge and stall, combustor blow out, fuel control run-down, instrumentation sensing errors, etc.).

19. CRITICAL POINT TESTING AT GROUND LEVEL. The applicant may test the engine at ground level conditions, provided the relevant engine operational factors of the critical points are reproduced in a relevant manner.

a. Test compensation. The applicant should compensate for differences between the critical point conditions and the test facility conditions. These differences may include:

(1) Air density. The critical point percentage of rain and hail concentration by weight should be reproduced during the test. For example, 20 g/m3 of rain at 20,000 feet is approximately three-percent water by weight. At sea level, this percentage of water requires nearly 40 g/m^3 to compensate for the higher air density (Refer to Appendix B, FIGURE B 1).

(2) Scoop factor. The appropriate rain and hail concentration amplification due to the scoop factor effect should be applied to further increase the quantities of rain and hail for the ground level tests. Determining this effect necessitates having knowledge of the inlet diffusing flow field throughout the engine power or thrust range and flight envelope.

(3) Engine **rotational** speeds. The engine speed for the ground level test should be no greater than the altitude critical point condition. This is particularly important for turbofan engines since rotational speed determines the rain and hail centrifuging effects which prevent some of the rain and hail **from** reaching the engine core. The rain and hail concentrations may be adjusted to compensate for any necessary deviation from critical point rotational speeds.

(4) Variable systems. All variable systems, such as engine bleeds, whose position can **affect** engine operation in rain and hail, should be set in the position associated with the critical point.

(5) Engine power extraction. It should be shown by analysis or test that sufficient margin exists for extraction of the representative electrical or shaft power loads and service air bleeds.

(6) **Thermodynamic cycle** differences. There may be thermodynamic cycle differences between the test point and the critical point, which affect the operability of the engine. There should be compensation for these cycle differences, or it should be shown that these differences provide additional conservatism.

(7) **Enthalpy** of water. Rain and hail concentrations may be adjusted to ensure that the heat extraction resulting **from** their ingestion are the same as the critical point. If the ingestion of liquid water droplets is accepted (see paragraph 20 of this AC for compliance alternatives) for critical hail point testing, then the water concentration should, as a minimum, be increased to compensate for the heat of fusion of ice.

(8) Rain droplet breakup. In the ground level test environment, forces applied to accelerate the simulated rain droplets to flight speed, as well as shear forces between the droplets and the engine airflow, are likely to break up the droplets. This breakup can result in reduced conservatism due to additional centrifuging by the fan or propeller and spinner. The concentration of the rain may need to be increased to compensate for the added centrifuging resulting **from** ground level testing.

b. **Engine** test facility. The engine test facility should provide a uniform water droplet or hail spatial distribution within the critical area of a geometric plane within the engine inlet. These uniform spatial distributions need to be agreed to by the appropriate FAA ACO. The facility should also provide proper droplet or particle sizes, and proper velocity distributions, unless otherwise **justified,** in accordance with Appendix B.

c. Instrumentation. Instrumentation and data sampling rates should be sufficient to establish; rain and hail temperature and concentrations, particle velocities and size distributions, and engine response. Primary exhaust water to air ratio measurements, by way of gas sampling should be considered. Instrumentation accuracy and repeatability should be demonstrated by suitable means.

d. Test procedure. The test procedure should consider the following for operability critical point tests, and for the thermal shock (rain only) critical point test:

(1) Stabilize the engine at the critical point conditions.

(2) Take steady-state data readings before introducing rain or hail.

(3) Start continuous transient data recording prior to initiation of rain or hail flow.

(4) Establish altitude equivalent rain or hail flow at proper inlet velocity and size distribution.

(5) Conduct operability critical point tests at the following steady-state conditions:

(a) Deliver rain for a minimum of three minutes, at the altitude equivalent concentration defined in Appendix B, FIGURE B 1 and Table B 1.

(b) Deliver hail for a minimum of 30 seconds, at the altitude equivalent concentration defined in Appendix B, FIGURE B 1 and Table B2.

(6) When testing low power critical points (i.e., minimum flameout and/or run-down margin), conduct tests with ingestion at the following transient conditions:

(a) Accelerate the engine with one-second throttle movement to rated takeoff power or thrust from the minimum rotor speed defined by the critical point analysis.

(b) Decelerate the engine with one-second throttle movement from an appropriate power or thrust setting (e.g., 50-percent rated takeoff power or thrust) to the minimum rotor speed defined by the critical point analysis.

(c) If test conditions or test facility limitations prevent transient testing as defined above, the applicant may propose alternative test criteria. This alternative test criteria must provide test criteria (and any complementary substantiation) which validates that the engine has sufficient operability margins to account for likely flight operations such as missed approaches (i.e., go-around) and likely throttle movements during descent.

(7) Conduct the thermal shock critical point test by delivering rain for three minutes at the critical power or thrust condition, following a normal stabilization period without water ingestion. The maximum rain ingestion rate should occur within five seconds from onset.

e. Probable factors. It should be demonstrated by test or analysis, that the engine tested in accordance with paragraph 19.d. of this AC would have operated acceptably if exposed to other probable factors associated with a rain or hail encounters. These other probable factors would include, but are not be limited to; typical engine performance losses, installation effects, and typical auto-throttle power excursions.

f. Acceptance criteria. Acceptable engine operation excludes flameout, run-down, continued or non-recoverable surge or stall, or loss of acceleration and deceleration capability. A momentary surge or stall that arrests itself without operational intervention (e.g., without throttle manipulation) is usually acceptable (see paragraph 19.f.(1), below). If, after the test, it is found that damage has occurred, further running or other evidence may be required to show that subsequent failures resulting from the damage are unlikely to occur before the damage is rectified. Engine performance should be measured before and after the rain and hail ingestion tests to assess steady state performance changes. Data should be normalized according to the applicant's standard practices, and the evaluation of sustained loss or degradation of power or thrust should encompass the full range of engine power or thrust.

(1) Use of auto-recovery systems during certification testing. Auto-recovery systems typically include auto-relight systems, stall recovery systems, or any other engine system intended to restore operability of an engine following a flameout, surge or stall. Although auto-recovery systems do not need to be disabled during rain and hail certification testing, a test result that indicates that the auto-recovery system interceded to

recover from a flameout, even a momentary flameout, would be an unacceptable result. This is also true for unrecoverable surges, stalls or run-downs. Engine systems that preemptively prepare the engine for operation in inclement weather via control system or variable geometry system **reconfigurations,** may be enabled during rain and hail certification testing.

(a) A momentary **flameout** of only one to two seconds duration may be considered acceptable if it can be shown that it is unnoticeable to the flight crew and does not **affect aircraft** operation. Additionally, if a momentary **flameout** does occur, an analysis should be performed to account for the worst case combination of engine bleeds, component performance, and expected transients, to show an adequate relight margin in all configurations and expected conditions. If compliance to these criteria is dependent upon the functioning of an auto-recovery system, then availability of this system is considered critical for dispatch and should therefore have a higher standard of reliability. Since the rule precludes flameout, then this momentary **flameout** would necessarily need to be analyzed and potentially reviewed against, and potentially accepted to part 21, paragraph 2 1.2 1 **(b)(1),** as an equivalent level of safety, if it is judged to meet that criteria, and should be so notated on the Type Certificate Data Sheet.

(2) Sustained power or thrust loss. As a result of the test, any shifts or errors in measured thrust or power, which occur against the primary thrust or power set parameter(s) (i.e., fan speed, engine pressure ratio, torque, **shaft** horsepower), should be limited to three-percent for aircraft safety.

(3) Power or thrust degradation. A change of engine corrected thrust or power of up to lo-percent from rated or pretest levels, excluding the primary thrust or power setting parameter, is acceptable provided the criteria for sustained power or thrust loss is met. This change in performance is based on the applicant's standard performance parameters (e.g., exhaust gas temperature, rotor speed, etc.).

20. OTHER COMPLIANCE ALTERNATIVES. Analysis may be used in place of, or in combination with, engine testing to demonstrate compliance with the requirements. The analytical methods used should have a sufficient validation basis to justify the accuracy of the predictions, or be shown to yield conservative results. The amount of validation (e.g., engine test, rig test, experimental test, etc.) should be proportional to the complexity of the analytical methods used, and to the criticality of the particular calculation to the prediction of engine operability.

SECTION 5. GUIDANCE ON ENGINES FOR SUPERSONIC AIRPLANES

21. GENERAL. This Section provides additional guidance to the requirements of § 33.78(c), titled, Engines for supersonic airplanes. This additional guidance is intended to outline an acceptable harmonized compliance plan which is consistent with the intent of JAR-E 790(c), while not altering the requirement or intent of § 33.78(c).

(1) Compliance requirements. In addition to complying with paragraphs (a)(l) and (a)(2) of § 33.78, a separate supersonic airplane engine test is required to be conducted with three hailstones ingested at supersonic cruise velocity, except as otherwise noted in § 33.78(c).

(2) Operating conditions. The engine's rotor speeds, component loadings, and component temperatures for this test should be representative of supersonic cruise flight operation.

(3) Hailstone ingestion sequence. The hailstones should be ingested in a rapid sequence to simulate an in-flight hailstone encounter.

(4) Alternate large hailstone option. Section 33.78(c) allows an alternate hailstone test where three large hailstones may be ingested in a rapid sequence at subsonic velocities. It should be shown that for this alternate subsonic test, the ingestion is equivalent to the applicable supersonic ingestion with respect to engine component loadings and strengths, the kinetic energy of hailstones and their depth of penetration into the engine.

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